

CONCURRENT SCHEDULES: UNDERMATCHING AND CONTROL BY PREVIOUS EXPERIMENTAL CONDITIONS

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Five pigeons were trained on concurrent variable-interval schedules. A series of conditions in which the ratio of reinforcement rates on two keys was progressively increased and then decreased was arranged twice. The birds were then exposed to an irregular sequence of conditions. Each condition in which reinforcement was available on both keys lasted six sessions. Performance in the first, third, and sixth sessions after a condition change was analyzed. Following a condition change, preference was biased toward the preference in the last condition, but this effect largely disappeared before the sixth session of training. The birds' preferences also appeared less sensitive to reinforcement rates in early sessions after a transition. Preference in a session was a function of both the reinforcements in that session and the reinforcements obtained in as many as four or five previous sessions. The effects of reinforcements in previous sessions could be summarized by the performance in the immediately preceding session, giving a relatively simple relation between present performance and a combination of present reinforcement and prior session performance. While such hysteresis could cause undermatching when only a small number of sessions are arranged in a condition, undermatching in a stable-state performance probably arises elsewhere.

Key words: concurrent schedules, variable-interval schedules, transition performance, hysteresis, undermatching, pecking, pigeons

Undermatching in concurrent schedules is a systematic deviation away from a matching relation toward indifference. The amount of the deviation away from matching is a function of the ratio of reinforcement rates obtained by the animal and is thus discriminable from bias, which is a deviation independent of the reinforcement ratio (Baum, 1974). If P refers to responses and R to reinforcements, and subscripts 1 and 2 denote the two operants,

$$\frac{P_1}{P_2} = c \left[\frac{R_1}{R_2} \right]^a. \quad (1)$$

The constant c represents bias, and the constant a measures the sensitivity to reinforcement. A sensitivity of less than 1.0 is termed undermatching. A number of explanations of undermatching have been suggested in the literature (Baum, 1974; de Villiers, 1977; Keller

& Gollub, 1977). In this paper, we are concerned with the suggestion that the sequence of experimental conditions to which animals are exposed produces undermatching (de Villiers, 1977; Keller & Gollub, 1977).

Keller and Gollub suggested that when an animal was exposed to a series of differing experimental conditions, the sensitivity with which behavior changed with changing reinforcement was decreased. This was supported by experiments which showed greater undermatching when pigeons were exposed to a series of conditions than when each pigeon was exposed only to equal reinforcement rates followed by unequal reinforcement rates. This conclusion is clouded by the possibility that the animals in the second experiment had different biases rather than different sensitivities to reinforcement.

de Villiers (1977) preferred an explanation of undermatching in terms of bias rather than sensitivity. He suggested that the sequence in which animals are exposed to different reinforcement rates might produce undermatching. The most usual experimental design in this area is to expose the animals to the conditions

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in an irregular sequence, often trying to reverse preference between the operants in each successive condition. Usually the same sequence is used for each animal. On the one hand, if the animals' preference (i.e., P_1/P_2) in a condition was biased by exposure to a previous condition—that is, if preference showed hysteresis—undermatching would result under this design. If, on the other hand, conditions were conducted in an ascending and descending sequence of reinforcement ratios, the same bias might not effect sensitivity. It should lead to a consistent deviation of data points below the matching line in the ascending sequence and above the matching line in the descending sequence. Results supporting this suggestion were reported by Baum (1972). The present experiment is concerned with these specific questions: (a) Is preference affected by previous experimental conditions? and (b) If so, how long does this effect last?

A group of pigeons was exposed to a series of experimental conditions in which the ratio of reinforcement rates on two keys was increased and then decreased, and this whole sequence was then repeated. The birds were then exposed to a series of conditions arranged in an irregular order. Except when one schedule was extinction, the conditions lasted six sessions.

A MODEL FOR HYSTERESIS

It is useful to specify at this stage the type of model we might expect to apply to hysteresis. We shall assume that preference in Session n is determined by the ratio of reinforcements obtained in Session n in combination with the reinforcement ratios from previous sessions ($n-1$, $n-2$, etc.). We shall further assume that the contributions of the present and previous sessions are differentially weighted, with a greater weighting for more recent sessions. Last, we shall assume that these contributions combine according to the product-sum rule which applies to the combination of other independent variables (e.g., magnitude of reinforcement, delay of reinforcement, and quality of reinforcement) which control preference (Baum & Rachlin, 1969; Hollard & Davison, 1971; Miller, 1976). Using the same variables as in Equation 1, with further bracketed subscripts indicating session number, this model can be written:

$$\frac{P_{1(n)}}{P_{2(n)}} = k \left[\frac{R_{1(n)}}{R_{2(n)}} \right]^a \cdot \left[\frac{R_{1(n-1)}}{R_{2(n-1)}} \right]^b \cdot \left[\frac{R_{1(n-2)}}{R_{2(n-2)}} \right]^c \dots \quad (2)$$

We would expect that $a > b > c$. If these exponents did not fall to zero over a long sequence of sessions, then, over an irregular sequence of experimental conditions, undermatching could be produced in the stable performance. The implications of this model seem intuitively correct. Following a transition between experimental conditions, preference would stabilize over a number of experimental sessions and thereafter remain constant. One implication is, however, clearly wrong. A transition from concurrent variable interval (*conc VI*) Extinction schedules to *conc VI VI* schedules is predicted to produce extreme preference (an infinite response ratio) for j sessions after the transition, where j is the number of terms in Equation 2 before the exponent is zero.

An important implication of Equation 2 is that the reinforcement contributions of previous sessions can be fully summarized by performance in the single most recent ($n-1$)th session:

$$\frac{P_{1(n)}}{P_{2(n)}} = k \left[\frac{R_{1(n)}}{R_{2(n)}} \right]^a \cdot \left[\frac{P_{1(n-1)}}{P_{2(n-1)}} \right]^b, \quad (3)$$

where, of course, the performance in the ($n-1$)th session is controlled via Equation 2 by the reinforcement ratios in that session and previous sessions. This model has fewer difficulties with transitions from *conc VI* Extinction because of the finding that preference ratios in such schedules are seldom infinite.

METHOD

Subjects

Five homing pigeons with four years' experience on *conc VI VI* schedules (Hunter & Davison, 1978) were maintained at $80\% \pm 15$ g of their free-feeding weights. Bird H1 sustained a foot injury part way through the experiment, and data obtained following this are not reported here.

Apparatus and Procedure

The chamber, of internal dimensions 37-cm high by 31-cm wide by 33-cm deep, was situated remote from conventional relay control equipment. It was fitted with a fan which

Table 1

Sequence of experimental conditions for each bird. Six sessions training were given in each condition. Schedule values are given in seconds.

Condition	Left key	Right key
1	Ext	VI 60
2	VI 380	VI 90
3	VI 90	VI 45
4	VI 120	VI 120
5	VI 45	VI 90
6	VI 90	VI 380
7	VI 60	Ext
8	VI 45	VI 380
9	VI 90	VI 380
10	VI 45	VI 90
11	VI 120	VI 120
12	VI 90	VI 45
13	VI 380	VI 90
14	Ext	VI 60
15	VI 380	VI 90
16	VI 90	VI 45
17	VI 120	VI 120
18	VI 45	VI 90
19	VI 90	VI 380
20	VI 60	Ext
21	VI 90	VI 380
22	VI 45	VI 90
23	VI 120	VI 120
24	VI 90	VI 45
25	VI 380	VI 90
26	Ext	VI 60
27	VI 120	VI 120
28	VI 380	VI 90
29	VI 45	VI 90
30	Ext	VI 60
31	VI 90	VI 380
32	VI 90	VI 45
33	VI 60	Ext

helped mask external noise. In the chamber were two response keys, 2 cm in diameter, 23 cm apart, and 25 cm from the grid floor, which, when they were illuminated white, were operated by pecks exceeding .1 *N*. Each peck to the illuminated keys turned off both keys for 30 msec, and was reinforced on each key according to two nonindependent (Stubbs & Pliskoff, 1969) VI schedules. These schedules were randomized from the first 12 terms of an arithmetic progression with the shortest interval one-twelfth the average interval. A changeover delay (Herrnstein, 1961) arranged that responses to either of the keys could not be reinforced, even if reinforcement had been set up by the associated tape, until 3 sec had elapsed since the first peck to that key after pecking the other key.

No illumination other than the keylights

was arranged in the chamber, and sessions terminated in blackout after 30 reinforcements (3-sec access to wheat) had been obtained. Except for conditions in which extinction was arranged on one key, each condition (Table 1) was in effect for six sessions. In extinction conditions, performance was allowed to stabilize according to a criterion which required that, for each bird, the median relative preference over five sessions did not differ from the median of the previous five sessions by more than 5% on five occasions. A new condition was begun when all birds had met this criterion. Stabilizing according to this criterion took between 16 and 18 sessions in all extinction conditions. In each session, data on the number of responses, the time spent responding (from the first peck on one key to the first peck on the other), and the reinforcements obtained on each key were recorded.

In the first 14 conditions of the experiment, the reinforcement ratios on the 2 schedules were successively changed by .3 logarithmic steps (excepting steps to and from extinction conditions) to produce an ascending and descending sequence of reinforcement ratios. A replication (Conditions 15 to 25) was carried out because an extra step was inserted in the first descending sequence by error. In Conditions 26 to 33, the same schedules used in the first part of the experiment were arranged in an irregular order.

RESULTS

The data from the first, third, and sixth sessions of each condition were analyzed. The preference data from the sixth sessions are shown in Figure 1 (ascending and descending reinforcement ratios) and Figure 2 (irregular sequence). In these figures, the logarithm of the ratio of responses emitted is plotted as a function of the logarithm of the ratio of reinforcements obtained on the two keys. Straight lines were fitted to these data by the method of least squares, and the equations of these lines are shown in the figures. Because extinction conditions have infinite reinforcement ratios, these data cannot be shown. Hence, no data points are common to both the ascending and descending fitted lines in Figure 1.

The generally small standard errors of estimate shown in the figures demonstrate that the sixth session data were reasonably well

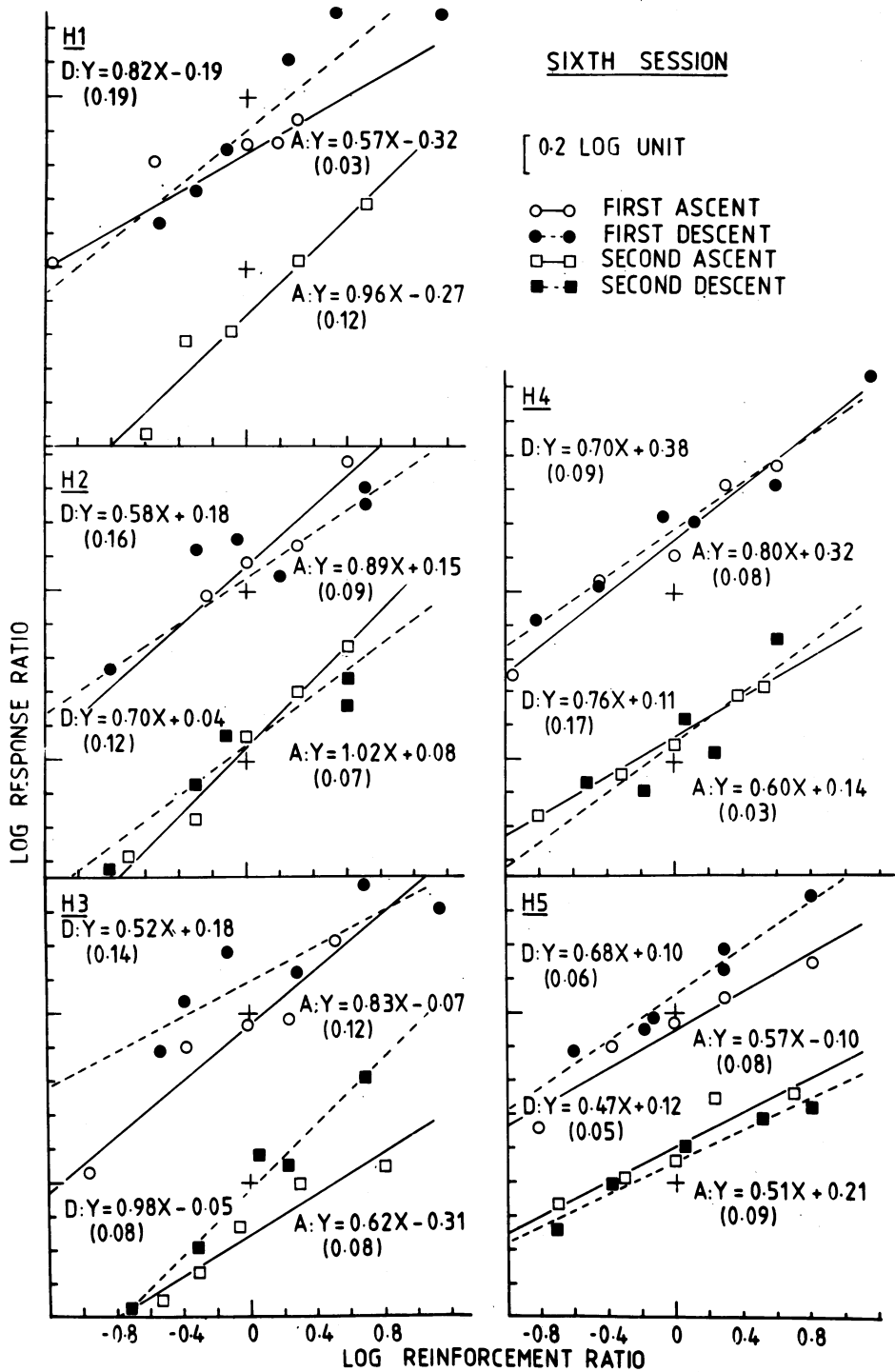


Fig. 1. Data from the sixth session of training on the ascending and descending sequences of reinforcement ratios. Log ratios of emitted responses are plotted as a function of log ratios of obtained reinforcements on the two keys, and the second ascending/descending sequence is displayed 1.0 log units below the first. Straight lines fitted by the method of least squares are shown with their equations and, below these, the standard error of the estimate. Ascending data equations are prefixed A, and descending equations are prefixed D. The origin of each pair of lines is shown by a cross.

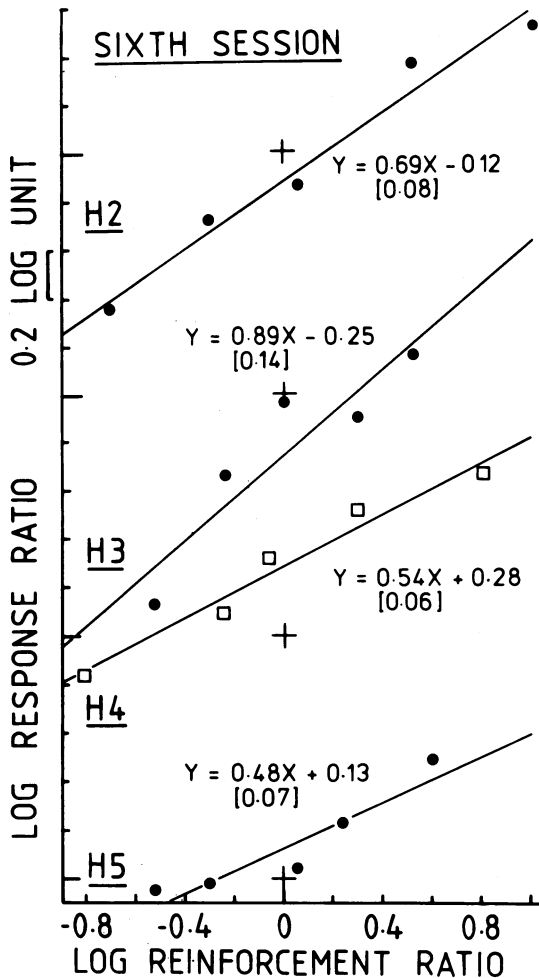


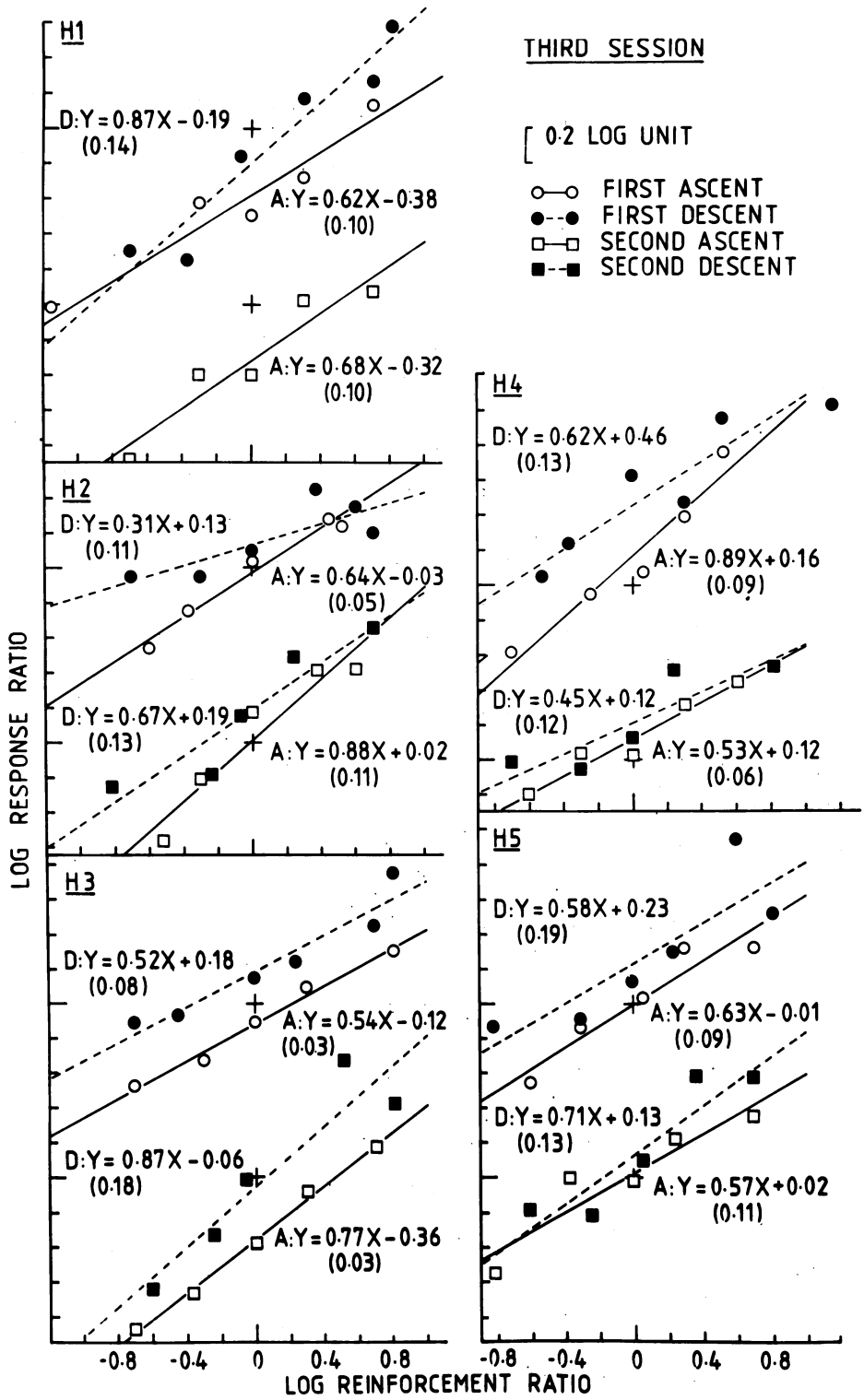
Fig. 2. Data from the sixth session of training on the irregular sequence of conditions. Log ratios of emitted responses are plotted as a function of log ratios of obtained reinforcements on the two keys, and each birds' data are displaced 1.0 log units down the y axis. Straight lines fitted by the method of least squares are shown with their equations and, below these, the standard error of the estimate. The origin of each graph is shown by a cross.

fitted by straight lines. There were some exceptions, for example, bird H2 in the first descent and bird H4 in the second descent. It should be noted that there can be no estimate of variability in the present data, and also that the fits of the straight lines should be somewhat worse than those usually reported which are based on means of three or five sessions. The slopes of the fitted lines were mostly less than 1.0 and were similar to those usually found for *conc* VI VI schedule performance (Lobb & Davison, 1975; Myers &

Myers, 1977). Sign tests (Siegel, 1956) showed that there was no significant difference in either slope or intercept between the lines fitted to the ascending and descending data (9 comparisons). For all birds except H4, the slope obtained from the irregular sequence of conditions (Figure 2) fell within the range of slopes obtained for the same bird in the ascending and descending sequences (Figure 1). For all birds except H2, the intercept obtained from the irregular sequence fell within the range obtained for the same bird in the ascending and descending sequences.

The third session data are shown in Figures 3 and 4 plotted in the same way as the sixth session data. Sign tests showed that there was no significant difference between the slopes for the ascending and descending sequences (nine comparisons). Whereas the average slope for the sixth session data was .70 (ascending .71, descending .69), the average for the third session performances was .65 (ascending .67, descending .62). A Sign test on the intercepts of the lines fitted in Figure 3 showed that those for the ascending sequence data were smaller than those for the descending sequence ($p < .05$). The average intercept for the sixth session performances was .05 (ascending .01, descending .10); those for Session 3 averaged .04 (ascending -.06, descending .14). Generally, the straight lines fitted to the Session 3 performances fitted as well as they did for the Session 6 performances. The slopes of the lines fitted to the irregular sequence data (Figure 4) fell within the range of slopes from the ascending and descending sequences (Figure 3) with the exception of H5, and the intercepts fell within the range of the ascending and descending sequences for two birds with no consistent direction of deviation for the other two.

Figures 5 and 6 show preferences in the first session of exposure to an experimental condition. Again, Sign tests showed that there was no significant difference between the slopes of the lines fitted to the ascending and descending data (average .55, ascending .50, descending .60), although the slopes were smaller than those obtained from the third or sixth session of training. As with the third session data, the ascending intercepts were, in every comparison, smaller than the descending intercepts (Sign test $p < .05$). The average intercept was .05, and the ascending and descending intercepts were -.17 and .26 respectively. The



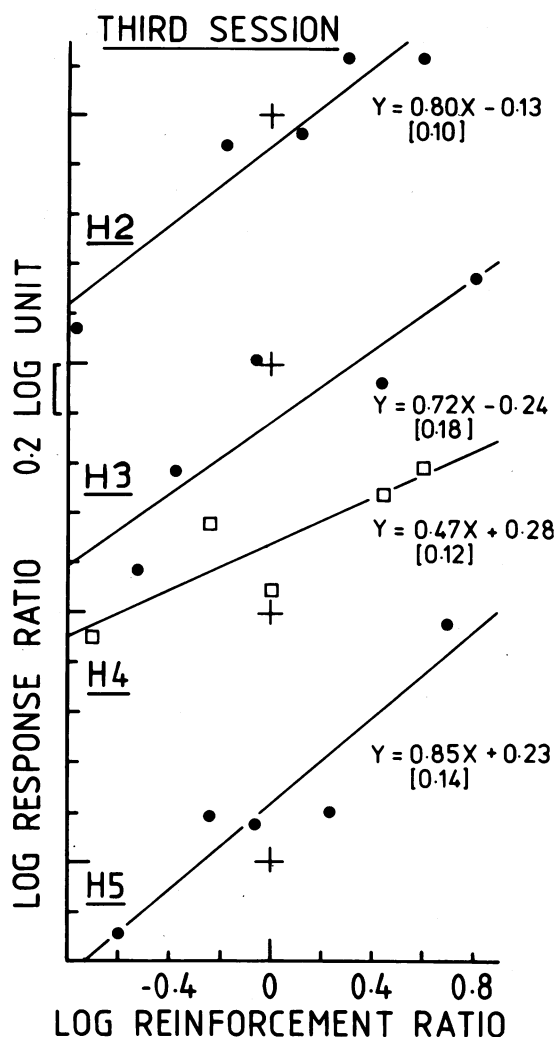


Fig. 4. Data from the third session of training on the irregular sequence of conditions. For further details, see Fig. 2.

straight lines fitted the ascending and descending data fairly well, though not as well as they did the third and sixth session data. However, straight lines fitted the irregular sequence data (Figure 6) poorly, and we put no confidence in the slopes and intercepts of these fits.

The changes in slope and intercept of the fitted lines from the first, through the third, to the sixth session performances was assessed using a nonparametric trend test (Ferguson, 1976). This showed a significant trend for the

intercept of the fitted lines in Figures 1, 3, and 5 to decrease toward zero (indifference) as training progressed (19 comparisons, 3 conditions, $z = 4.9$, $p < .01$). A similar test showed a significant tendency for the slopes of the fitted lines to increase with more exposure to a condition (19 comparisons, 3 conditions, $z = 2.16$, $p < .02$). The irregular presentation series, not included in the above analysis, shows the same effects.

Time allocation data are not reported here inasmuch as they showed the same major effects in every case.

Equation 3, discussed earlier, states that present performance is a function of present reinforcement ratio in combination with the response ratio in the previous session. The adequacy of this equation was assessed using multiple linear regression on the data from the irregular sequence of conditions. (This procedure could not give unbiased results with the ascending and descending sequence data because response and reinforcement ratios in successive conditions were necessarily highly correlated.) The dependent variable was the logarithm of the present session response ratio, and the independent variables were the logarithms of the present session reinforcement ratio, the previous session ($n - 1$) response ratio, and the response ratios from sessions ($n - 2$) and ($n - 3$). These latter two independent variables were included simply to check that their influence was negligible. The data from every session in which extinction was not arranged were used, but stable final session extinction condition performances were used as independent variables. The number of data points was about 30 per bird, a few having been lost through jammed counters and experimenter errors. The results of the multiple linear regression are shown in Table 2. Statistically, with this number of data points, the proportion of variance accounted for must exceed .24 to attain significance at the 1% level. The smallest variance proportion accounted for was .76, and the standard errors of estimate were small. Table 2 shows that the present reinforcement ratio contributed strongly to the present performance and that the previous session response ratio contributed less strongly. As expected, present performance

Fig. 3. Data from the third session of training on the ascending and descending sequence of reinforcement ratios. For further details, see Fig. 1.

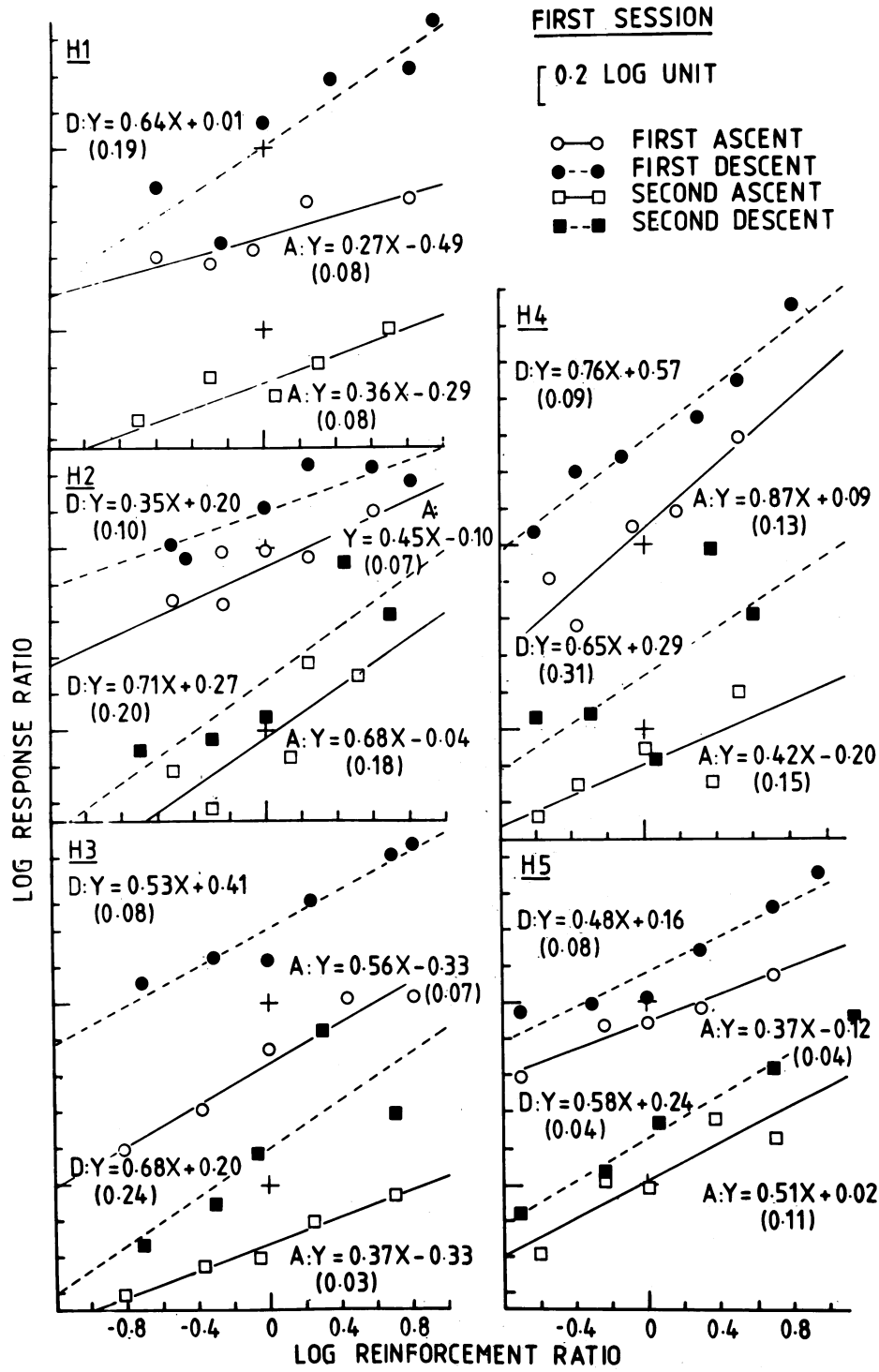


Fig. 5. Data from the first session of training on the ascending and descending sequence of reinforcement ratios. For further details, see Fig. 1.

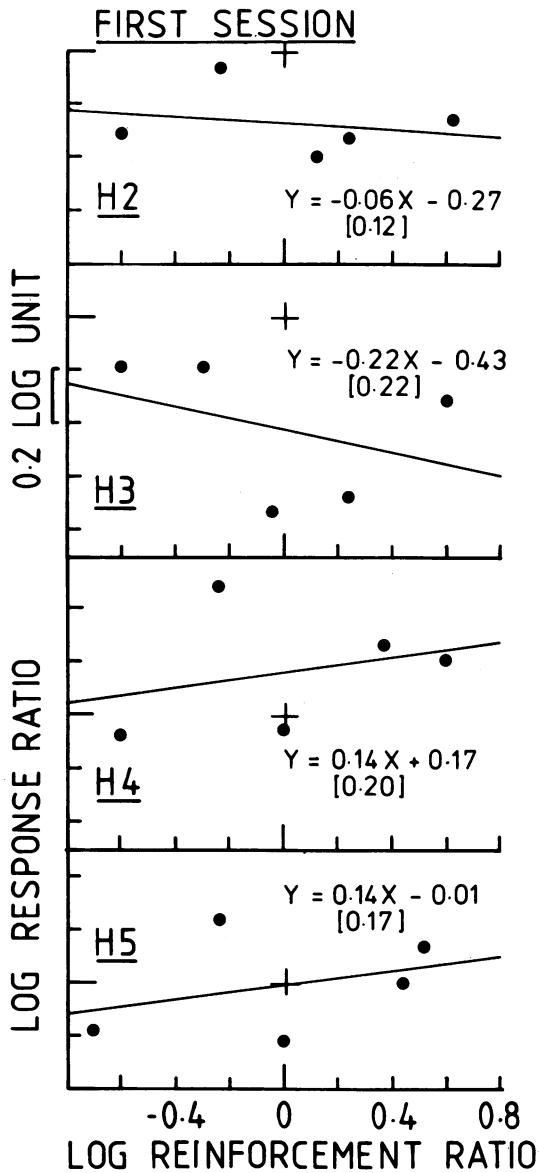


Fig. 6. Data from the first session of training on the irregular sequence of conditions. For further details, see Fig. 2.

was unaffected by performance in sessions prior to the previous session. On the average the exponent a for present reinforcement rate was .48, and the exponent b for previous session performance was .28.

It is interesting to see how the changes in preference over the sessions of exposure to a condition were reflected in the overall response rates on each key in the ascending and descending sequences. Figure 7 shows some

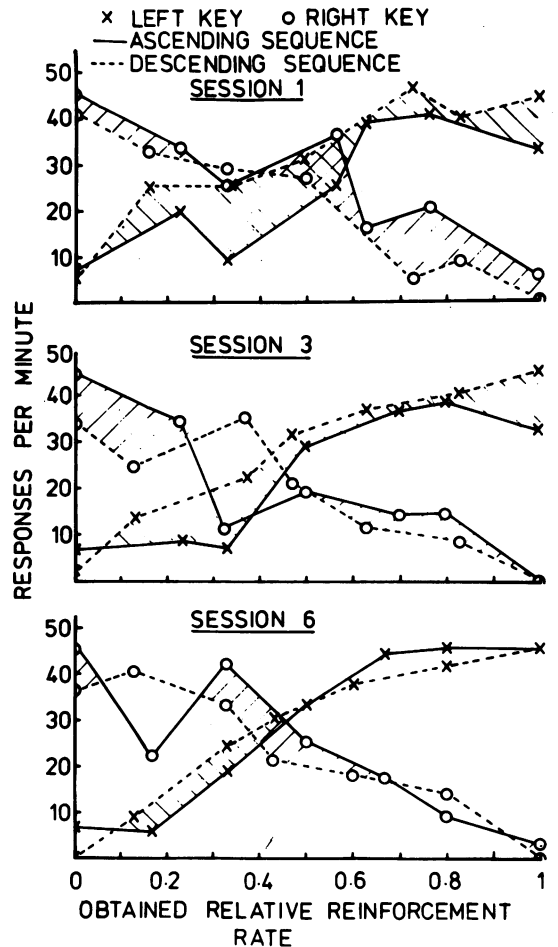


Fig. 7. Responses per minute on the left and right keys as a function of the relative reinforcement rate (number of reinforcements on the left key divided by total reinforcements) obtained for responding on the left key. The data shown are for bird H2 in conditions 14 through 26, with the ascending and descending sequence of conditions, and the data from the first, third and sixth sessions, shown separately. In each graph, the starting points of both the ascending and descending sequence is performance in the final stable session of conditions in which extinction was arranged on one key (Conditions 14 and 20). The end points are, as appropriate, the first, third, and sixth sessions of performance in the extinction conditions (Conditions 20 and 26). Crosshatching shows the separation of ascending and descending data when these differed in a direction consistent with an effect of the previous condition.

typical data obtained during the second ascent and descent. The data obtained from the first, third, and sixth sessions all show the usual trend of increasing response rates on a key as the relative reinforcement rate on that key increased (Catania, 1963). The data differed,

Table 2

The contribution to current-session preference of the current-session reinforcement ratio (session n), and the preferences in sessions $(n - 1)$, $(n - 2)$, and $(n - 3)$. The data are logarithmic ratios from each session of the irregular sequence of conditions, but extinction session preferences are not used as the dependent variable. Also shown are the logarithmic intercept, the standard error of each estimate and the total variance accounted for.

Bird	Exponents				Intercept	Variance accounted for
	Session n	Session $(n - 1)$	Session $(n - 2)$	Session $(n - 3)$		
H2	.59	.18	.04	-.01	-.10	.91
(SE)	(.05)	(.04)	(.04)	(.04)	(.03)	
H3	.42	.52	-.12	-.05	-.16	.83
(SE)	(.08)	(.10)	(.10)	(.07)	(.04)	
H4	.45	.13	-.03	.03	.24	.83
(SE)	(.05)	(.05)	(.03)	(.02)	(.02)	
H5	.47	.28	.03	-.07	.07	.76
(SE)	(.08)	(.09)	(.10)	(.07)	(.03)	

however, in the way in which the data from a session was influenced by previous conditions. Figure 7 clearly shows that, in the first session, response rates under increasing relative reinforcement rates tended to fall below those from decreasing relative reinforcement rates for both keys. This effect, shown by the crosshatched areas, decreased over the six sessions of training. The bias caused by condition changes is thus clearly represented in overall response rates on each key.

DISCUSSION

The present experiment has shown a number of useful facts about *conc* VI performance in transition. By the sixth session of training on a condition, preference seemed to be approaching stability (cf. Shull & Pliskoff, 1967). At this point, the intercept differences between the ascending and descending sequence data (Figure 1) had largely disappeared, and the slopes (Figures 1 and 2) of the fitted lines were approaching values similar to those often reported for stable-state concurrent variable-interval performance (Lobb & Davison, 1975). In earlier sessions, as predicted by Equation 2, transitions produced a bias toward preference in previous conditions, shown in the ascending and descending sequence data as a biased matching line and in the irregular sequence data as an abnormally low sensitivity (Figures 3, 4, 5, and 6). For the ascending and descending sequence data, longer training also produced steeper matching lines, but at each ses-

sion in training the ascending and descending lines were not significantly different in slope. We can state, then, with reasonable certainty, that the bias or hysteresis resulting from a transition lasted at least three sessions but had largely disappeared by six sessions, and that the effect of a particular sessional reinforcement ratio decreased progressively with distance from the present session. We are not in a position to generalize these results very far because it is possible that a 20-session exposure to an experimental condition could produce more and longer lasting hysteresis than a 6-session exposure. Although the ascending and descending biases were not significantly different by the sixth session, the continuing increase in sensitivity to reinforcement means that the present data cannot be used to justify brief exposures to experimental conditions.

Bias caused by transitions between conditions could also be affected by the absolute reinforcement rates in the concurrent schedules. In view of previous results (Fantino, Squires, Delbruck, & Peterson, 1972) which showed that preference was unaffected by total reinforcement rates when changing reinforcement ratios were taken into account, we did not maintain a constant total reinforcement rate. The most deviant total reinforcement rate was in the conditions in which VI 90-sec and VI 45-sec were arranged. Neither the preference data (Figures 1 to 6) nor the overall response rate data (Figure 7) showed any consistent data deviation in these conditions, suggesting that the effects found here could be independent of total reinforcement rate.

The results of the multiple linear regression on the irregular sequence data confirmed the generalization of Equation 2 given in Equation 3. An approximate verbal summary is that the present preference is related to the square root of the present session reinforcement ratio and the fourth root of the previous session response ratio. Again, we cannot be confident that, for example, shorter sessions would not change this relation. However, Equation 3 with these parameters has a number of interesting properties. First, it predicts a critically damped change and an asymptotic steady-state error (undermatching) in response ratios following a transition, and the response ratio measure is predicted to stabilize in four to five sessions. Second, the asymptotic level of the response ratio is quite independent of the response ratio in the previous condition although, of course, the intervening levels are dependent on the previous preference. Third, Equation 3 with these parameters and with $k = 1$ predicts a stable-state matching performance with no bias and a slope or sensitivity of .67. (The slope is independent of the combinations of the schedules used.) After 6 sessions of training (Figures 1 and 2), 10 of the fitted lines had slopes of less than this value and 13 had greater slopes.

Some other properties of Equation 3 are of interest. If $a + b$ is greater than 1.0, overmatching results; if these sum to less than 1.0, undermatching results. The speed at which performance will stabilize depends on the relative size of a and b ; with a relatively large, performance stabilizes quickly.

Equation 3 with the obtained parameters, which was derived from the irregular sequence data, accurately predicts the intercept changes over sessions shown in Figures 1, 3, and 5. Strictly applied, however, it does not predict the increases in the slopes of the matching lines from the first to the sixth session of training but, rather, predicts slope decreases. The problem arises in the prediction of preference after a transition from conditions which contain extinction as one schedule. If extinction session performances are not used to predict subsequent preference, the predicted slopes over six sessions of training increase in a way very similar to the data obtained here. This result seems to suggest that extinction conditions may not control subsequent behavior in the same way as conditions

in which reinforcement is available on both keys. The implication may be that hysteresis is a failure to discriminate changed conditions, with *conc* VI Extinction conditions not falling on this stimulus dimension.

A reviewer suggested that the difficulties encountered by Equations 2 and 3 with transitions from Extinction could be overcome by considering an additive, rather than a multiplicative, model. The type he suggested was

$$\frac{P_{1(n)}}{P_{2(n)}} = k \left[\frac{R_{1(n)} + bR_{1(n-1)}}{R_{2(n)} + bR_{2(n-1)}} \dots \right]^a.$$

Unfortunately, when transitions from extinctions are taken into account, this model also predicts a decrease in the slope of matching lines with increased training. Apart from this difficulty common to both models, the additive model has the disadvantage of not conforming to the product-sum rule (Baum & Rachlin, 1969), the currently accepted means of combining different parameters of reinforcement.

In summary, preference in a session either may be predicted from the reinforcement ratio in that session in conjunction with the reinforcement ratios in the previous four or five sessions (Equation 2); or it may be predicted from the reinforcement ratio in that session in conjunction with the response ratio in the immediately preceding session (Equation 3). Because these models, and the additive model, have incomplete generality, they are tenable only as descriptive rules of thumb. Rather than making further assumptions to increase their generality, we are now carrying out much more detailed analyses of transition performances.

The present results showed that transitions do bias subsequent preferences, but that the effect disappears quickly with training and would be absent in stable-state data. Thus de Villiers' (1977) suggestion that undermatching is caused by biases arising from the order in which the experimental conditions are run to stability is not supported by these data. Although it would be possible to argue for a different type of hysteresis operating at a much more molar level—determining, for example, the level at which the next condition will stabilize—such an argument is not supported by our finding that the slopes for the sixth session data were similar for the ascend-

ing, descending, and irregular sequences. The present data, incidentally, also seem contrary to another suggestion made by de Villiers that exposure to other types of schedules may cause undermatching. The birds used here had been exposed only to *conc VI* schedules. Another possible explanation of undermatching is the continuing increase in sensitivity to reinforcement from the first through the sixth session of training. This trend is probably entirely accounted for by the biases in the data from the previous conditions inasmuch as the sensitivities to reinforcement in the sixth sessions (when bias was absent) were close to those normally obtained in *conc VI VI* schedules after 15 to 20 sessions of training.

Perhaps the most important aspect of the present data is that they demonstrate that orderly and quantifiable changes do occur between stable performances on different experimental conditions. They open the way to a more detailed and potentially fruitful prediction of behavior in transition or *learning*.

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